Effect of horizontal pick and place locations on shoulder kinematics.

Könemann, R.; Bosch, T.; Kingma, I.; van Dieen, J.H.; de Looze, M.P.

published in
Ergonomics
2015

DOI (link to publisher)
10.1080/00140139.2014.968636

Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: http://www.tandfonline.com/loi/terg20

Effect of horizontal pick and place locations on shoulder kinematics

R. Könemann, T. Bosch, I. Kingma, J.H. Van Dieën & M.P. De Looze

Ergonomics, 2015
Vol. 58, No. 2, 195–207, http://dx.doi.org/10.1080/00140139.2014.968636

Effect of horizontal pick and place locations on shoulder kinematics

R. Könemann[a,b]*, T. Bosch[a,b], I. Kingma[c], J.H. Van Dieën[b,c] and M.P. De Looze[a,b,c]

[a]*TNO, P.O. Box 3005, 2301 DA, Leiden, The Netherlands;* [b]*Body@Work, Research Centre Physical Activity, Work and Health, Amsterdam, The Netherlands;* [c]*Faculty of Human Movement Sciences, Research Institute Move, VU University, Amsterdam, The Netherlands*

(*Received 18 July 2013; accepted 15 September 2014*)

In this study the effects of horizontal bin locations in an order picking workstation on upper arm elevation, trunk inclination and hand use were investigated. Eight subjects moved (self-paced) light or heavy products (0.2 and 3.0 kg) from a central product bin to an inner or outer order bin (at 60 or 150 cm) on the left or right side of the workstation, while movements were recorded. The outer compared to inner bin location resulted in more upper arm elevation and trunk inclination per work cycle, both in terms of number of peak values and in terms of time integrals of angles (which is a dose measure over time). Considering the peak values and time integrals per minute (instead of per work cycle), these effects are reduced, due to the higher cycle times for outer bins. Hand use (left, right or both) was not affected by order bin locations.

Practitioner Summary: Workers in order picking workstations are exposed to long durations and high frequencies of arm movements. Horizontal compared to vertical bin placement minimises arm elevations, although the change from a 'standing' to a 'walking' situation also increases the postural load, but to a much lesser extent.

Keywords: order picking; workstation design; horizontal distance; movement strategy; hand use

1. Introduction

Monotonous activities involving repetitive movements of the hands and arms are increasingly common in various sectors of industry. This is mainly due to the frequent automation of significant parts of work processes. An example is the warehousing sector, where the so-called goods-to-man or parts-to-picker transportation systems (instead of 'man-to-goods') have been introduced (e.g. Bosch, De Looze, and Ten Hoor 2008). This implies that the order picker in automatic warehouses may now stand relatively still at a stationary workstation, picking products out of product bins and placing them into order bins, instead of moving around the warehouse to pick the products from the racks. Goods-to-man systems are commonly used for any product which fits, with one or multiple, in a standard sized product bin (for example 60 cm × 40 cm × 40 cm) and can be managed by hand (e.g. retail products, small automotive spare parts). The main advantage of goods-to-man systems is that they are very efficient, since workers are constantly picking (Anon 1986). At the same time, however, the workers are exposed to a long duration and high frequency of arm movements, as periods of loading of the upper extremities during picking and placing are no longer interspersed with periods of unloading while moving through the warehouse. Highly repetitive work with a lack of rest increases the risk of developing injury in the neck and shoulder (Van Rijn et al. 2010; Nordander et al. 2009; Sommerich, McGlothlin, and Marras 1993).

For work which involves high-frequency arm movements, reducing the occurrence of stressful body postures (e.g. arm elevation, trunk inclination) is important (Strasser et al. 1989). This can be achieved with a well-designed workstation. In the case of a high-volume order picking workstation, a high number of bins (e.g. 5–8 bins) needs to be present at the same time. The design challenge here is to find the optimal locations for all these bins to minimise arm elevations and trunk inclination. Many high-volume order picking workstations are based on a two-layer design (vertical plane), where workers pick products from bins at a high vertical level (just below shoulder height) and place products into bins at a low level (waist height). This concept minimises walking but high arm elevations and trunk inclination will occur frequently (Bosch, De Looze, and Ten Hoor 2008). Another concept is a one-layer design (horizontal plane), where all bins are placed on the optimal vertical level (waist height). Consequently, bins are positioned over a larger horizontal range, in a lateral direction, introducing some walking.

The physical load effects of bin locations in a vertical plane are generally straightforward: with increasing working heights the upper arm angle increases, resulting in higher internal shoulder loads (Garg, Hegmann, and Kapellusch 2006; Hagberg 1981; Nussbaum et al. 2001). It is also clear that repetitive elevation of the upper arms, above shoulder level, increases the risk for developing shoulder injury (Fagarasanu and Kumar 2003).

*Corresponding author. Email: reinier.konemann@tno.nl

It is questionable what the effects are of bin locations in a horizontal plane (from within reach to several steps to the outside). The positioning of bins at waist level potentially minimises upper arm elevations, though they are still repetitive. But how does distance between the bins affect workers' movements within their workstation and, in turn, how this does affect their physical loading pattern. For example, while placing products in an outer bin, workers may choose to walk and reach over to place the product, instead of walking until standing right in front of the bin and not having to reach. This reaching involves more stressful upper arm and trunk postures. Rosenbaum (2008) and Rosenbaum, Brach, and Semenov (2011) studied reaching and walking behaviours and they observed a preference for walking above reaching within their experimental set-up. The preference for either reaching or walking might be affected by product weight. Faber, Kingma, and Van Dieën (2007) found that in a lifting task, subjects preferred to reach further for lighter products.

Horizontal pick and place locations may also affect the way hands are used. One may expect that if pick and place locations are within reach, workers might use one hand for efficiency reasons. However, when workers have to walk several steps from pick to place location, it is possible to change the product between hands. Hand use is an important variable with respect to shoulder load. If only one hand is used, all load of the task is on one shoulder, while variation in hand use distributes the load over both shoulders. Hand use, in uni-manual or bi-manual, was previously studied by Gorman and Crites (2013) and Srinivasan, Martin, and Reed (2013), but only for fine motor coordination tasks. These results are not comparable with the gross picking movements in this study.

Hence, workstation engineering and behavioural factors determine the intensity and temporal aspects of the biomechanical load on the upper extremities, and thereby determine the risk of developing neck and shoulder injury (e.g. Finnsgård and Wänström 2013; Baril-Gingras and Lortie 1995). Therefore, the aim of the study was to assess the effect of bin location, in a one-layer design order picking workstation, on upper arm and trunk kinematics; and on hand use. The second aim was to investigate how product weight affects these variables and interacts with lateral bin location effects.

Regarding the kinematics, we studied the number of peak angles of upper arm elevation and trunk inclination, in line with risk assessment methods such as rapid upper limb assessment (RULA) (McAtamney and Corlett 1993) and occupational repetitive action (OCRA) (Occhipinti 1998). We also studied a dose measure of physical loading over time, the time integral of upper arm elevation and trunk inclination, in line with risk assessment methods such as hand arm risicobeoordelings methode (HARM), in which the exposure to elevation and inclination over time is taken into account (Douwes and de Kraker 2014).

We hypothesised the following:

(1) A larger lateral order bin distance results in an increase of the time integral and number of peaks for upper arm elevation and trunk inclination per work cycle because, for efficiency, subjects could choose to reach further and walk less. The increase per unit of time is hypothesised to be less pronounced, because of longer work cycle times for the order bins at a larger lateral distance.
(2) Furthermore, we hypothesised that a larger lateral order bin distance increases variation in hand use. With pick and place locations within reach, subjects might use one hand for efficiency reasons.
(3) Finally, we hypothesised that the effects of lateral order bin distance (as described in the first hypothesis) are more pronounced for light products.

2. Methods

2.1. Participants

Eight healthy order pickers participated in the study (four males and four females). They were all familiar with order picking, but had no specific experience with the order picking station that was used in this study. The average stature of the participants was 1.74 (standard deviation (SD) 0.11) m, body weight 67 (SD 12) kg and age 29 (SD 9) years. All participants were right handed. Participants gave their written informed consent prior to the start of the study.

2.2. Procedure and task

The participants performed a task on a high-volume order picking workstation, where products had to be moved manually from centrally located product bins to order bins on the sides. Eight conditions were performed with four different order bin locations (inner/outer and left/right) and two product weights (light/heavy). The product and order bins were dimensioned as follows 60 cm × 40 cm × 32 cm (length, width, height). For the inner order bin locations, the product and order bins were about 10 cm apart and the distance between centre points of the bins was about 60 cm. For the outer order bin locations, the product and order bins were 100 cm apart and the distance between the centre points was about 150 cm. The light product was a bundle of six rolls of sticky tape with a total weight of about 0.2 kg and dimensions of 6 cm × 11 cm (diameter, height). The heavy product was a tray with six cans, weighting about 3.0 kg, with dimensions of 28 cm × 10 cm × 8 cm (length, width and height).

The height-adjustable platform in front of the workstation was used to set the workstation height (i.e. top of the bins) just below elbow height of the participant. The order of the eight conditions was randomly varied across participants. After each condition, 5 min of rest was given before starting the next condition. Participants were asked to maintain a constant self-selected work pace that they could sustain in case of an 8-h working day. Products had to be placed carefully in the order bin. No further instructions with regard to movement technique were provided. To become familiar with the experimental equipment, the task and to offset a learning effect across conditions, a training session was performed before the start of the experiment.

The workstation including the location of the bins is illustrated in Figure 1. Figure 2 illustrates the three activities that were performed within one work cycle in the experiment. Each cycle started with the appearance of a number on a centrally placed screen, shown to the participant standing in front of the product bins. The first hand-arm activity was to pick one product out of the right or left central product bin (depending on the order bin location where the product had to be placed, right product bin for right order bins and vice versa). Participants had to call the number from the screen aloud while performing the first activity, to simulate that workers have to process the number of products to be picked from the product bin in a real-work setting (Figure 3). The second hand-arm activity was to move the product and place it into one of the order bins. The third and final hand-arm activity was to press a button, to confirm the placement of the product in the order bin. The buttons were positioned in front of the order bins. After pressing the button, the subjects returned to the central computer screen, and initiated the next work cycle.

In the conditions with the light products, 30 work cycles were performed, and 20 work cycles with the heavy products. The number of cycles for the heavy products was lower, to have comparable condition durations and because of a limited

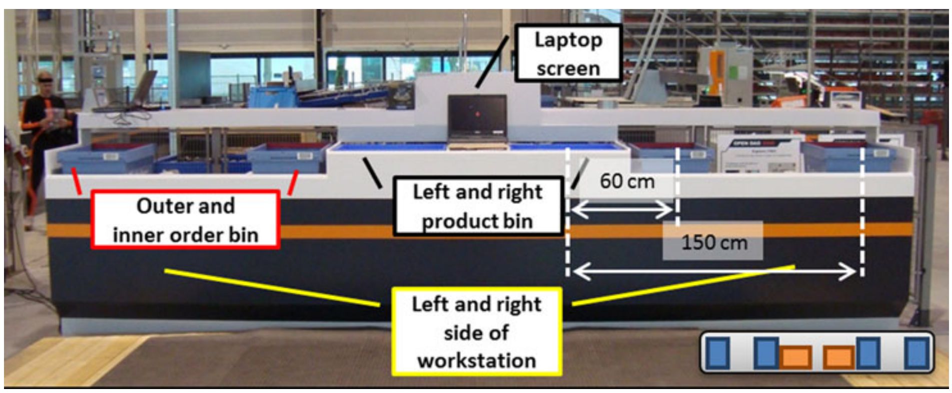


Figure 1. The high-volume picking station (5 m wide) shows the two centrally located product bins and an inner and outer order bins on the left and right side (a schematic representation in the top left, blue squares represent product bins).

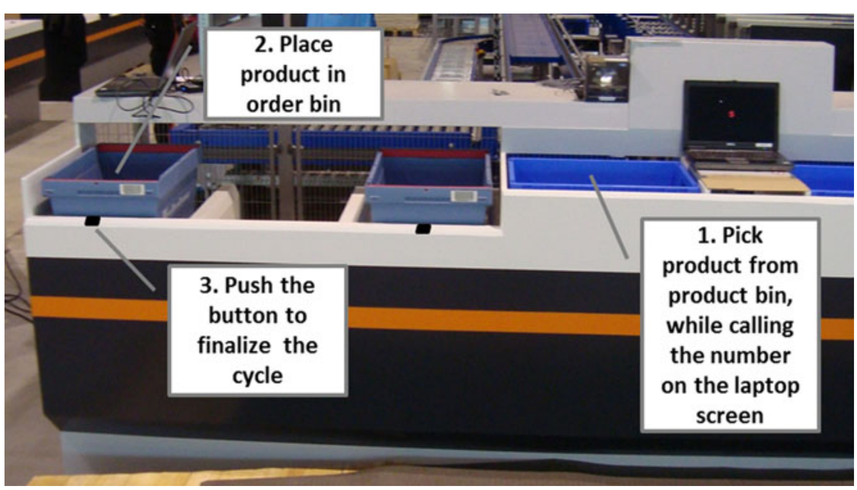


Figure 2. Picking and placing activities visualised for the left outer order bin, with the black confirmation button in front of the order bin. After each pick and place action, participants returned to product bin position.

Figure 3. A participant wearing the Xsens® suit during the experiment, while picking a product from the product bin and calling out the number show on the screen.

bin capacity. Because of the limited capacity of the bins, the product and order bins were changed once by the experimenter, during the conditions with the heavy product. The bins were changed without delaying the participants' pace.

2.3. *Measurements*

The movements of the participants were recorded by a full body inertial motion capture system (MVN, Xsens® Technologies, Enschede, The Netherlands). This system comprises a suit, equipped with 17 MTx sensors (Figure 3). The sensors comprise 3D gyroscopes, 3D accelerometers and 3D magnetometers (Roetenberg, Luinge, and Slycke 2009). By use of a Kalman filter (Kalman 1960), the system uses these nine signals for each sensor to calculate sensor orientation at each instant of time. Raw data are transmitted by a Bluetooth connection to a laptop computer on which data are processed and visualised. Prior to the experiment, participants' body dimensions and calibration poses were measured according to Xsens® calibration protocol with the MVN software (MVN Biomech 3.1), to fit and scale the MVN Biomech model to the participant. The MVN Fusion Engine calculates the position and orientation of each body segment, with respect to an earth-fixed reference coordinate system. The MVN Fusion Engine used the calibration poses to determine the direction of the axes of each segment. Positions of anatomical landmarks were not measured directly, but derived from sensor orientations in combination with the biomechanical model. The anatomical landmarks were collected at a sample rate of 120 Hz and exported in a C3D format. A dedicated Matlab program (version 2010b, The MathWorks, Inc., Natick, MA, USA) was used to calculate the left and right upper arm elevations and the trunk inclination angles. The left and right upper arm elevation angles were defined as the enclosed angles between a vertical downward vector through the acromion and a vector from the acromion to the average of the medial and lateral epicondyle of the elbow. The trunk inclination angle was defined as the enclosed angle between a vertical upward vector through the L5 spinal process and a vector from the L5 spinal process to the C7 spinal process.

2.4. *Data analysis*

For upper arm and trunk load, guidelines (e.g. ISO 11228-3 2007) generally consider an enclosed angle between upper arm (or trunk) and the vertical axis of 20° as a threshold, implying that upper arm elevations (or trunk inclinations) below this

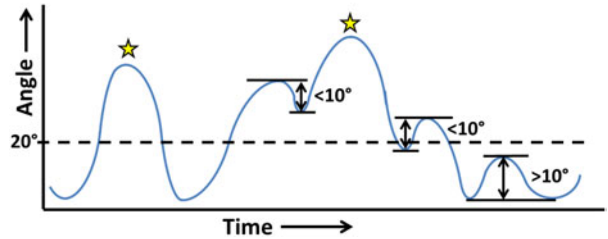


Figure 4. Visualisation of peak angle definition. The dashed line is the threshold of 20° for peak angles and the yellow stars represent peak angles. Marked areas are part of the integral above the guideline threshold.

value are considered 'safe, not affecting health', irrespective of the number of the upper arm elevations per minute and task duration. Therefore, as an exposure measure, the integral above the threshold of 20° was calculated, for the upper arm elevation angle and trunk inclination angle.

The number of upper arm elevations and number of trunk inclinations were calculated by peak counting. A peak angle was the largest angle in between two local minima. A peak angle was counted, when it was at least 15° higher than both surrounding local minima (movement threshold). The movement threshold of 15° was used to select clearly observable movements. The threshold value was extrapolated from the 'just noticeable difference' for trunk posture of 2° to 7°, described by Weir et al. (2007). When the local minimum following the peak angle was within the 15° difference, only the largest local maximum with a following local minimum at least 15° lower was considered a peak angle (Figure 4). Only peak angles above the threshold of 20° were analysed (CEN 2005). This definition generally led to two or three peak angles during each work cycle, most probably associated with the activities of picking, placing and/or pushing the button.

Four parameters were determined for left and right upper arm elevations and trunk inclination, per condition: the time integral above 20° per minute (degree*s) and per cycle (degree*s) and the number of peaks above 20° per minute (#/min) and per cycle (#/work cycle).

To identify hand use, video recordings were made during the experiment. These recordings were visually inspected in order to score hand use for each picking and placing action. Picking and placing actions could be done with one hand, right (R) or left (L), or with both hands (B). The definition of the overall movement strategy was a combination of picking and placing hand use during one cycle. For example, a right hand pick and a left hand placing will add up to a 'RL' movement strategy. With the two activities and three types of hand use, this results in nine possible strategies. In a condition with 30 cycles, there are 29 possibilities for a strategy change. Strategy change is defined here as the change in overall movement strategy between subsequent cycles.

2.5. Statistics

For right and left arm elevations and trunk inclination, the time integral and the number of peaks (both per minute and per cycle) were analysed using repeated-measures ANOVA (ANOVA 1, with independent variables lateral order bin DISTANCE (inner/outer), product and order bin SIDE (left/right) and product WEIGHT (light/heavy)). The percentage of activities in which the right and left hands were used was analysed separately using a similar repeated-measures ANOVA, with ACTIVITIES (picking/placing) as an additional factor (ANOVA 2). To analyse the number of strategy changes per condition, a third repeated-measures ANOVA (ANOVA 3) was used with lateral order bin DISTANCE (inner/outer), order bin SIDE (left/right) and product WEIGHT (light/heavy) as independent factors.

The p-value was based on the degrees of freedom corrected with Greenhouse–Geisser's epsilon to compensate for the effects of violations of the sphericity assumption when necessary (Twisk 2003). For the significant interaction effects, Bonferonni-corrected t-tests were used as post-hoc test for the comparison of means. Significance was accepted at $p < 0.05$.

3. Results

3.1. Characteristics of exposure to arm and trunk loads

The average work cycle duration for conditions with inner order bins was 3.6 s (SD 0.8) and that for outer bins was 4.8 s (SD 0.9), for light products it was 3.8 s (SD 0.8) and for heavy products it was 4.6 s (SD 1.1). All 30 work cycles for light products and 20 work cycles heavy products were included for further analysis. The average peak amplitude of right and left upper arm elevations was 34.7° (SD 4.9) and 32.9° (SD 6.5), respectively. The average peak amplitude for trunk inclination was 24.7° (SD 2.4).

Table 1a. Results of ANOVA 1 on the time integral and number of peaks per cycle for upper arm elevations and trunk inclinations.

	Upper arm elevation (left)				Upper arm elevation (right)				Trunk inclination			
	Time integral		Number of peaks		Time integral		Number of peaks		Time integral		Number of peaks	
Per cycle	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Distance (inner/outer)	9.3	**0.019**	29.4	**0.001**	5.6	**0.050**	65.2	**0.000**	6.1	**0.043**	12.1	**0.010**
Weight (light/heavy)	2.3	0.174	1.7	0.230	1.8	0.218	9.0	**0.020**	0.9	0.363	0.1	0.753
Side (left/right)	13.9	**0.007**	0.3	0.622	3.0	0.125	0.0	0.934	1.9	0.208	1.5	0.266
Distance*weight	0.2	0.694	2.3	0.174	1.7	0.239	1.9	0.209	2.3	0.170	4.4	0.074
Distance*side	2.9	0.131	0.0	0.847	3.0	0.129	0.3	0.597	0.0	0.903	0.4	0.557
Weight*side	1.2	0.302	0.5	0.492	0.9	0.383	5.1	0.058	0.9	0.382	1.6	0.241
Distance*weight*side	0.2	0.705	1.5	0.264	0.2	0.655	1.7	0.233	2.5	0.159	0.2	0.653

Note: Significant effects ($p < 0.05$) are indicated by bold values.

3.2. Lateral order bin distance

3.2.1. Upper arm elevation

For the time integral and the number of peaks per cycle, we found a significant effect of the lateral order bin DISTANCE. Both the time integral and the number of peaks per cycle of the left and right upper arm elevations were higher for the outer bins than for the inner order bins (Table 1a and Figure 5(a),(b)).

For the results over time, the number of peaks per minute was significantly higher for the outer order bins (Table 1b and Figure 6(b)) and the left upper arm elevation frequency showed a trend towards significance. In contrast to the within-cycle results, we did not find an increase for the integral (per minute) of the right and left upper arm elevations, for outer bins compared with inner order bins (Table 1b and Figure 6(a)).

3.2.2. Trunk inclination

Lateral order bin DISTANCE significantly affected trunk inclination time integral and number of peaks per cycle (Table 1a and Figure 5(a),(b)). In line with our hypothesis, a higher time integral and a higher number of peaks per cycle were found for the outer order bins.

No significant effect was found on trunk inclination time integral per minute. Lateral order bin DISTANCE did have a main effect on the number of peak trunk inclinations per minute. The number of peaks per minute was significantly higher for the outer bins, as shown in Figure 8.

3.2.3. Hand use and strategy change

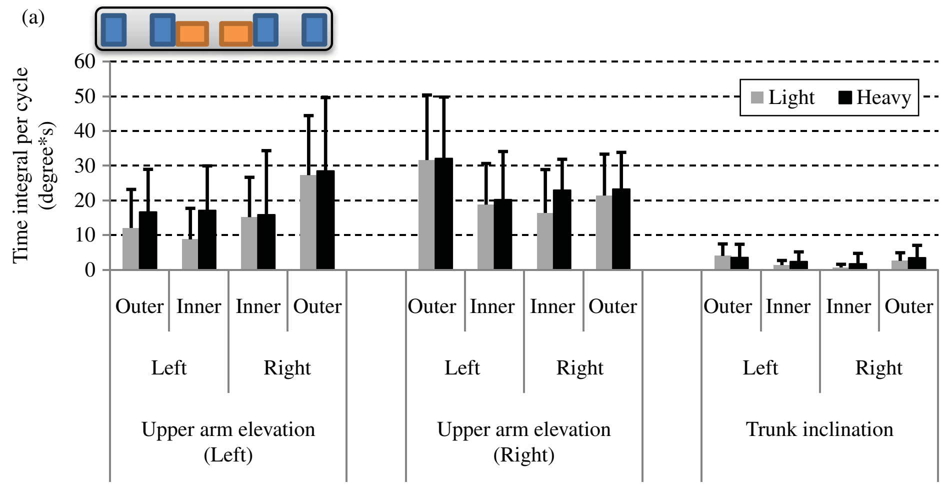
Summed over picking and placing activities, participants used their right hand in 72%, their left hand in 26% and both hands in only 2% of the activities. Large SDs were found for the hand use of the right and left hands (Figure 7). No specific ANOVAs were applied on activities performed with both hands because of this low prevalence. The use of both hands only occurred with heavy products and mainly during picking (Figure 7). The percentages of right and left hands use were analysed using ANOVA 2 (Table 2), and the number of strategy changes was analysed using ANOVA 3 (Table 3). No significant effects of lateral order bin distance were found for hand use and strategy change. Only a main effect of ACTIVITY was found for the percentage right hand use ($p = 0.038$). The placing activity was performed more frequently with the right hand (83%) than the picking activity (65%). A significant three-way interaction between ACTIVITY, SIDE and DISTANCE was found for the percentage of hand use, for the right and left hands. Only for the right hand significant results were found in post-hoc testing. Post-hoc testing indicated no significant effect on percentage right hand use for order bin DISTANCE in any of the specific ACTIVITY/SIDE combinations.

3.3. Product weight

The time integral and the number of peaks per cycle indicated an effect of product WEIGHT, only for number of peak right upper arm elevations (Table 1a and Figure 5(b)). Heavy products resulted in a higher number of peaks for right upper arm elevations than light products.

Product WEIGHT did not significantly affect the time integral and number of peaks per minute of left and right upper arm elevations and trunk inclination (Table 1b and Figure 6(a),(b)).

(a)



(b)

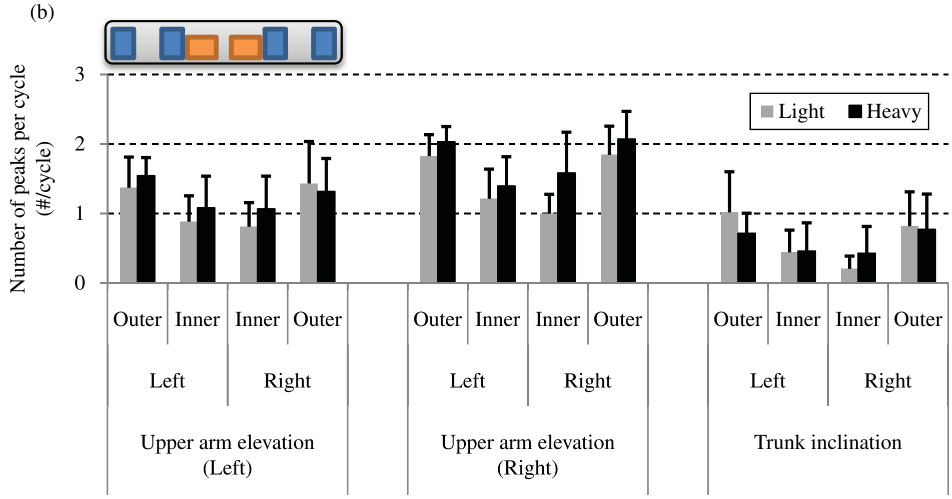


Figure 5. (a) Time integral, above 20°, per cycle of the left and right upper arm elevation angle and trunk inclination angle, for all conditions (DISTANCE: inner/outer; SIDE: left/right; WEIGHT: light/heavy). (b) Number of peaks, above 20°, per cycle, of left and right upper arm elevation peak angles and trunk inclination peak angles, for all conditions (DISTANCE: inner/outer; SIDE: left/right; WEIGHT: light/heavy). Error bars indicate the SD. Conditions are ordered in geographical position on the workstation (schematic representation in the top left, blue squares represent product bins).

Table 1b. Results of ANOVA 1 on the time integral and number of peaks per minute for upper arm elevation and trunk inclination.

	Upper arm elevation (left)				Upper arm elevation (right)				Trunk inclination			
	Time integral		Number of peaks		Time integral		Number of peaks		Time integral		Number of peaks	
Per minute	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Distance (inner/outer)	1.5	0.258	4.6	0.069	0.2	0.645	14.6	**0.007**	3.2	0.116	5.8	**0.047**
Weight (light/heavy)	0.0	0.860	0.6	0.447	0.4	0.538	0.1	0.772	0.1	0.754	2.2	0.185
Side (left/right)	13.6	**0.008**	0.5	0.521	3.6	0.099	0.3	0.619	2.5	0.161	3.9	0.089
Distance*weight	0.0	0.868	1.9	0.209	0.9	0.374	3.1	0.122	3.1	0.124	4.6	0.068
Distance*side	2.9	0.130	0.1	0.776	2.1	0.189	2.7	0.142	0.1	0.740	1.4	0.279
Weight*side	1.2	0.316	0.2	0.709	1.4	0.276	3.2	0.119	1.3	0.292	2.5	0.155
Distance*weight*side	0.5	0.486	0.6	0.460	0.2	0.686	1.1	0.323	7.2	0.032	0.1	0.823

Note: Significant effects ($p < 0.05$) are indicated by bold values.

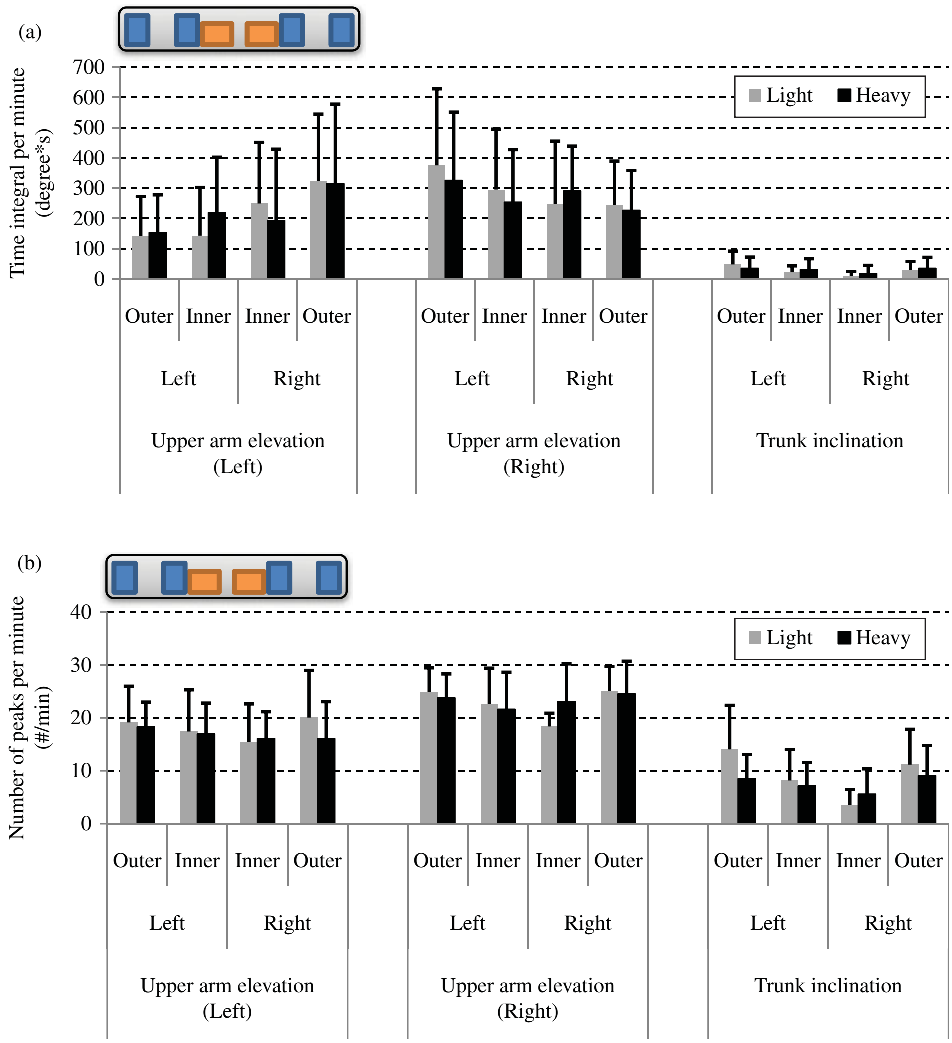


Figure 6. (a) Time integral, above 20°, per minute of the left and right upper arm elevation angle and trunk inclination angle, for all conditions (DISTANCE: inner/outer; SIDE: left/right; WEIGHT: light/heavy). (b) Number of peaks, above 20°, per minute, of left and right upper arm elevation peak angles and trunk inclination peak angles, for all conditions (DISTANCE: inner/outer; SIDE: left/right; WEIGHT: light/heavy). Error bars indicate the SD. Conditions are ordered in geographical position on the workstation (schematic representation in the top left, blue squares represent product bins).

We did not find a significant interaction effect between DISTANCE and WEIGHT, thus we could not confirm the hypothesis that light products would increase the effects of lateral bin distance. A three-way interaction was found for DISTANCE*WEIGHT*SIDE, but post-hoc testing did not indicate significant differences.

The percentage of cycles with a strategy change was affected by product WEIGHT (Table 3 and Figure 8), with more strategy changes occurring while picking and placing heavy products than while picking and placing light products (19% (SD 19) and 4% (SD 6) of the work cycles, respectively).

4. Discussion

In this study, we investigated the effects of lateral bin distance on upper arm and trunk kinematics and hand use strategy, in a one-layer order picking workstation. Furthermore, we investigated how product weight would interact with lateral bin distance. As hypothesised, a larger lateral distance to a placing location results, per cycle, in a higher time integral and a higher number of peaks for upper arm elevations (right and left) and trunk inclination. Effects on the time integrals and number of peaks, per minute, were less pronounced, because the longer cycle times for outer order bins compared to inner order bins counteracted the 'per cycle' effects. As a result, only the number of peaks per minute (and not the time integrals per minute) of upper arm elevations and trunk inclination was significantly higher or showed a trend towards significance.

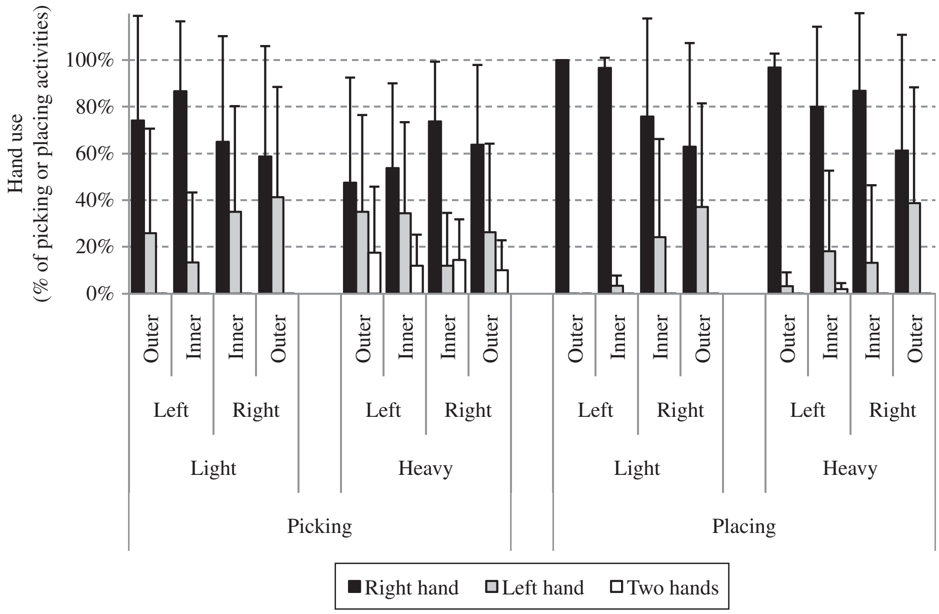


Figure 7. Hand use during picking and placing activities. Hand use prevalence of right, left, two hand(s), for all conditions (DISTANCE: inner/outer; SIDE: left/right; WEIGHT: light/heavy). Error bars indicate the SD.

Table 2. Results of ANOVA 2 on hand use.

	Right hand		Left hand	
	F	*p*	*F*	*p*
Activity (pick/place)	6.5	**0.038**	2.4	0.164
Side (left bin/right bin)	1.4	0.278	1.5	0.262
Distance (inner/outer)	3.3	0.114	2.7	0.146
Weight (light/heavy)	2.5	0.161	0.0	0.983
Activities*side	1.5	0.259	1.4	0.276
Activities*distance	0.4	0.544	0.3	0.625
Activities*weight	0.5	0.503	0.2	0.686
Side*distance	1.1	0.321	1.5	0.253
Side*weight	2.6	0.149	2.4	0.163
Distance*weight	0.0	0.898	0.0	0.924
Activities*side*distance	6.9	**0.034**	6.2	**0.042**
Activities*side*weight	2.3	0.177	1.9	0.216
Activities*distance*weight	0.0	0.920	0.1	0.749
Side*distance*weight	0.4	0.548	0.6	0.460
Activities*side*distance*weight	0.6	0.470	0.1	0.778

Note: Significant effects ($p < 0.05$) are indicated by bold values.

Table 3. Results of ANOVA 3 on strategy change in hand use.

	F	*p*
Distance (inner/outer)	3.3	0.113
Weight (light/heavy)	0.1	0.780
Side (left/right)	10.9	**0.013**
Distance*side	2.2	0.181
Distance*weight	3.7	0.095
Weight*side	0.6	0.476
Distance*side*weight	0.1	0.731

Note: Significant effects ($p < 0.05$) are indicated by bold values.

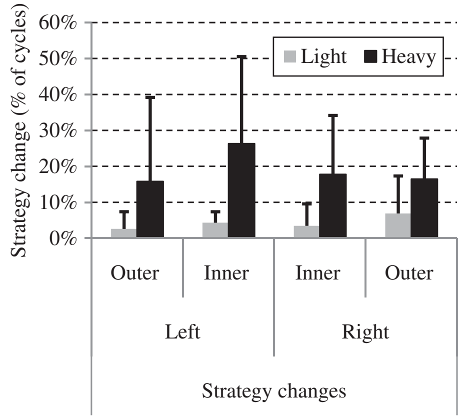


Figure 8. Percentage of work cycles with a strategy change compared with the previous work cycle, for all conditions (DISTANCE: inner/outer; SIDE: left/right; WEIGHT: light/heavy). Error bars indicate the SD.

Hand use was not affected by lateral bin distance, which is in contrast with our hypothesis, while product weight did affect strategy changes. In contrast with our third hypothesis, there was no interaction effect between lateral bin distance and product weight on the integral and frequency for upper arm elevations and trunk inclination.

4.1. Lateral bin distance on body angles per cycle

To discuss the effect of lateral bin distance on body angles, we first consider the time integral and the number of peaks per cycle. These results show that for the outer bins, which were a few steps away from the central position, the upper arms were elevated above 20° more frequently than the inner order bins, which were within direct reach of the subjects. In line with these higher number of peak elevations, we also observed a higher time integral of upper arm elevations above 20°.

As the vertical height of inner and outer bins is equal, there is no need for more upper arm elevations. Thus, the increased number of upper arm elevations is the result of a different picking and placing behaviour, freely chosen by the subjects and not enforced by the workstation design. This suggests that subjects do not walk the full distance to the product and order bins, but instead choose to reach for the bins, which requires more upper arm elevation. The same behavioural phenomenon explains the within-cycle results for the trunk: more trunk inclinations above 20° occur at the outer bins than at the inner bins.

The effect of lateral pick and place locations on body kinematics has been studied before, but these studies differed from this study in terms of the task characteristics. Jorgensen and Lavender (Jorgensen et al. 2005; Lavender and Johnson 2009) studied the task of moving boxes (10–16 kg) from one pallet or conveyer to another. These were not placed in line but at 90° or 180° location. These tasks involve more body rotation, more whole body movement (when picking and placing from low heights) and heavier weights than those of our study. In line with our study, these studies demonstrated a clear effect of distance on kinematics. Jorgensen et al. (2005) found that an increase in pallet distance, from 'no step' to 'one step', led to increased trunk angle velocities and accelerations (mainly for boxes placed at lower heights). Lavender and Johnson (2009) found that distance between conveyors had an effect on trunk twisting and lateral trunk bending motions during picking and placing. Twisting and bending motions were minimised at 1–1.25 m conveyor distance within the range of 0.5–1.75 m.

No other studies reported effects of distance on body kinematics in picking and placing tasks in which people had to walk. On the other hand, numerous studies have addressed reach distances and body kinematics in static tasks. In these studies, reach envelopes and reaching modes (arm and trunk involvement) with resulting normal/comfortable horizontal working area were determined (Gedliczka et al. 2007; Das and Behara 1995; Parkinson and Reed 2007; Gardner et al. 2001; Mark et al. 1997; O'Sullivan and Gallwey 2002; Choi et al. 2007).

In these studies, the freedom in behaviour is very limited compared with the workstations studied here at which people walk from one location to another (e.g. high volume order picking). Our study showed that the information on reach envelopes or reaching modes obtained from relatively static tasks cannot be extrapolated to more dynamic ('walking') tasks, where body angles of workers are influenced by walking and whole body movement strategies.

4.2. Lateral bin distance on body angles per minute

To determine the exposure to physical loading and related health risks, the time integral and the number of peaks per minute are more relevant than the results per cycle. Not surprisingly, we found that cycles for outer order bins were longer than for inner order bins. This counteracts the 'per cycle' effects of bin distance on both the time integral and number of peaks above 20°. As a result, we found no differences in time integral per minute between outer and inner order bins. Moreover, the differences in number of peaks per minute between inner and outer order bins were smaller than the differences per cycle: for both right upper arm elevations and trunk inclinations the difference is still significant, while for the left upper arm elevations a non-significant tendency was found.

In conclusion, longer work cycle for outer bins would imply a lower number of peaks and a smaller time integral, but these are neutralised by the movement strategy, more elevation and inclination for outer bins than for inner order bins. Picking workstations with higher distances to outer bin are not favourable from a performance as well as physical load perspective. Still, these types of workstations are required because of a large variety of products. If a large number of bins are required, it is much more favourable to place these in a lateral plane (minimal effects on upper arm elevation) than in the vertical plane (most likely large effects on upper arm elevation). Also the use of more forward-located bins, i.e. a double row of bins, might be expected to cause large effects on trunk inclination and arm elevation. The effect of positioning bins in the vertical plane, up to shoulder height, or forward horizontal plane, would lead to higher risk categories in risk assessments.

Results from this study need to be interpreted in the context that the work pace for this picking workstation is self-selected. Other workstations may have a fixed pace, which could limit the degrees of freedom if the pace is high. As a result, the limitation in the degrees of freedom might lead to less optimal postures (e.g. more trunk inclination) in exchange for faster movements. Furthermore, our study was limited to the lateral direction of the horizontal plane and not to the forward direction. Only two lateral bin distances were evaluated, with a largest distance of only 1.5 m, introducing only a minimal level of walking. Order picking workstations with more bins and up to double the width are available.

4.3. Bin locations and hand use

It was hypothesised that more variation in hand use would occur for outer than for inner bins, simply because people would have more time to vary and would choose to do so in order to prevent fatigue. This hypothesis was not confirmed.

As expected the preferred hand (the right hand for all subjects) was more frequently used than the non-preferred hand. In picking, 65% of the actions were performed using the right hand; in placing these actions were 83%. Moreover, with order bins on the left side, 93% of all placing actions into order bins were right handed. This high percentage can be explained by the fact that subjects walked parallel to the workstation to the left side with the right arm closest to the order bins. On the right side, placing actions are predominantly done with the right hand as well (72%) despite the fact that the left hand is in this case closer to the order bins. Possibly, most workers need their preferred hand to properly place a product in a partly filled order bin.

In other studies on stationary picking and placing, it has also been found that the preference hand is used more frequently, even at the contralateral side of the body (Gabbard and Rabb 2000; Stins, Kadar, and Costall 2001; Choi and Mark 2004). Rosenbaum (2008) and Rosenbaum, Brach, and Semenov (2011) found that walking path was also accommodated to the hand preference.

In general, workers appear to benefit to a limited extent from the opportunity to unload the upper extremities by alternating hand use.

4.4. Influence of product weight

We did not find an interaction effect of product weight with lateral order bin distance on body kinematics. Faber, Kingma, and Van Dieën (2007) also studied the effect of product weight on the movement strategy. Subjects picked building blocks of two different weights (6 kg vs. 16 kg) from pallets. For the lower compared with the higher weights, subjects chose to lift the blocks from a 10 cm larger distance from the pallet. In our study, a limited number of product weights were of a much lower order of magnitude, and possibly too low to find any differences in movement strategy (e.g. upper arm elevation and trunk inclination).

Product weight did have some effects on hand use. Picking and placing by two hands at the same time only occurred for the heavier (and larger) products (and mainly while picking). For lighter products, the pattern of hand use was highly uniform over the total duration of the task. For the heavier product, however, we observed more switches in hand use within the task.

In general, when handling relatively heavy products, tasks and workstations should be designed such that workers have the opportunity to choose which hand to use. This study showed that people make use of the opportunity to choose between hands for heavier products.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

We would like to thank Vanderlande Industries for their support. This work was financially supported by the European shared cost project 'Imoshion', funded under the Seventh Framework Programme for Research and Technological Development of the European Union.

References

Anon. 1986. "'Part-to-Man' Systems Keep Order Pickers Busy." *Modern Materials Handling* 41 (4): 26–30.

Baril-Gingras, G., and M. Lortie. 1995. "The Handling of Objects Other than Boxes: Univariate Analysis of Handling Techniques in a Large Transport Company." *Ergonomics* 38 (5): 905–925.

Bosch, T., M. P. De Looze, and M. C. Ten Hoor. 2008. "Sustained Performance and Workload in Order Picking." In *NES 2008 Abstracts: Ergonomics is a Lifestyle*, 77–78. Reykjavík: Gutenberg.

CEN. 2005. *EN 1005-4 – Safety of Machinery – Human Physical Performance. Part 4: Evaluation of Working Postures and Movements in Relation to Machinery*. Brussels: European Committee for Standardization.

Choi, H. J., and L. S. Mark. 2004. "Scaling Affordances for Human Reach Actions." *Human Movement Science* 23 (6): 785–806.

Choi, H. J., L. S. Mark, M. J. Dainoff, and C. Park. 2007. "Normative, Descriptive and Formative Approaches to Describing Normal Work Area." *Theoretical Issues in Ergonomics Science* 8 (1): 37–62.

Das, B., and D. N. Behara. 1995. "Determination of the Normal Horizontal Working Area: A New Model and Method." *Ergonomics* 38 (4): 734–748.

Douwes, M., and H. de Kraker. 2014. "Development of a Non-Expert Risk Assessment Method for Hand-Arm Related Tasks (HARM)." *International Journal of Industrial Ergonomics* 44 (2): 316–327.

Faber, G. S., I. Kingma, and J. H. Van Dieën. 2007. "The Effects of Ergonomic Interventions on Low Back Moments Are Attenuated by Changes in Lifting Behaviour." *Ergonomics* 50 (9): 1377–1391.

Fagarasanu, M., and S. Kumar. 2003. "Shoulder Musculoskeletal Disorders in Industrial and Office Work." *Journal of Musculoskeletal Research* 7 (1): 1–14.

Finnsgård, C., and C. Wänström. 2013. "Factors Impacting Manual Picking on Assembly Lines: An Experiment in the Automotive Industry." *International Journal of Production Research* 51 (6): 1789–1798.

Gabbard, C., and C. Rabb. 2000. "What Determines Choice of Limb for Unimanual Reaching Movements?" *Journal of General Psychology* 127 (2): 178–184.

Gardner, D. L., L. S. Mark, J. A. Ward, and H. Edkins. 2001. "How Do Task Characteristics Affect the Transitions Between Seated and Standing Reaches?" *Ecological Psychology* 13 (4): 245–274.

Garg, A., K. Hegmann, and J. Kapellusch. 2006. "Short-Cycle Overhead Work and Shoulder Girdle Muscle Fatigue." *International Journal of Industrial Ergonomics* 36 (6): 581–597.

Gedliczka, A., M. Konarska, K. Hamiga, Z. Machynia, K. Starzynska, J. Mircea, and C. Noworol. 2007. "Defining Space Models of Arm Reach Envelopes for Static Forced Postures." *Occupational Ergonomics* 7 (4): 219–231.

Gorman, J. C., and M. J. Crites. 2013. "Are Two Hands (from Different People) Better than One? Mode Effects and Differential Transfer Between Manual Coordination Modes." *Human Factors* 55 (4): 815–829.

Hagberg, Mats. 1981. "Work Load and Fatigue in Repetitive Arm Elevations." *Ergonomics* 24 (7): 543–555.

ISO 11228-3:2007. "Ergonomics – Manual Handling – Part 3: Handling of Low Loads at High Frequency."

Jorgensen, M. J., A. Handa, P. Veluswamy, and M. Bhatt. 2005. "The Effect of Pallet Distance on Torso Kinematics and Low Back Disorder Risk." *Ergonomics* 48 (8): 949–963.

Kalman, R. E. 1960. "A New Approach to Linear Filtering and Prediction Problems." *Journal of Basic Engineering* 82 (1): 35–45.

Lavender, S. A., and M. Johnson. 2009. "Is There a Lateral Transfer Distance That Minimizes Twisting and Lateral Bending Motions of the Spine?" *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 53 (14): 882.

Mark, L. S., K. Nemeth, D. Gardner, M. J. Dainoff, J. Paasche, M. Duffy, and K. Grandt. 1997. "Postural Dynamics and the Preferred Critical Boundary for Visually Guided Reaching." *Journal of Experimental Psychology: Human Perception and Performance* 23 (5): 1365–1379.

McAtamney, L., and E. N. Corlett. 1993. "RULA: A Survey Method for the Investigation of Work-Related Upper Limb Disorders." *Applied Ergonomics* 24 (2): 91–99.

Nordander, C., K. Ohlsson, I. Åkesson, I. Arvidsson, I. Balogh, G.-Å. Hansson, U. Stromberg, R. Rittner, and S. Skerfving. 2009. "Risk of Musculoskeletal Disorders among Females and Males in Repetitive/Constrained Work." *Ergonomics* 52 (10): 1226–1239.

Nussbaum, M. A., L. L. Clark, M. A. Lanza, and K. M. Rice. 2001. "Fatigue and Endurance Limits During Intermittent Overhead Work." *AIHAJ – American Industrial Hygiene Association* 62 (4): 446–456.

Occhipinti, E. 1998. "OCRA: A Concise Index for the Assessment of Exposure to Repetitive Movements of the Upper Limbs." *Ergonomics* 41 (9): 1290–1311.

O'Sullivan, L. W., and T. J. Gallwey. 2002. "Effects of Gender and Reach Distance on Risks of Musculoskeletal Injuries in an Assembly Task." *International Journal of Industrial Ergonomics* 29 (2): 61–71.

Parkinson, M. B., and M. P. Reed. 2007. "Standing Reach Envelopes Incorporating Anthropometric Variance and Postural Cost." SAE Technical Paper 2007-01-2482.

Roetenberg, D., H. Luinge, and P. Slycke. 2009. *Xsens MVN: Full 6DOF Human Motion Tracking Using Miniature Inertial Sensors*. Enschede: Xsens Motion Technologies BV, Tech. Rep.

Rosenbaum, D. A. 2008. "Reaching While Walking: Reaching Distance Costs More than Walking Distance." *Psychonomic Bulletin and Review* 15 (6): 1100–1104.

Rosenbaum, D. A., M. Brach, and A. Semenov. 2011. "Behavioral Ecology Meets Motor Behavior: Choosing Between Walking and Reaching Paths." *Journal of Motor Behavior* 43 (2): 131–136.

Sommerich, C. M., J. D. McGlothlin, and W. S. Marras. 1993. "Occupational Risk Factors Associated with Soft Tissue Disorders of the Shoulder: A Review of Recent Investigations in the Literature." *Ergonomics* 36 (6): 697–717.

Srinivasan, D., B. J. Martin, and M. P. Reed. 2013. "Effects of Task Characteristics on Unimanual and Bimanual Movement Times." *Ergonomics* 56 (4): 612–622.

Stins, J. F., E. E. Kadar, and A. Costall. 2001. "A Kinematic Analysis of Hand Selection in a Reaching Task." *Laterality* 6 (4): 347–367.

Strasser, H., E. Keller, K.-W. Muller, and J. Ernst. 1989. "Local Muscular Strain Dependent on the Direction of Horizontal Arm Movements." *Ergonomics* 32 (7): 899–910.

Twisk, J. W. R. 2003. *Applied Longitudinal Data Analysis for Epidemiology: A Practical Guide*. Cambridge, UK: Cambridge University Press.

Van Rijn, R. M., B. M. Huisstede, B. W. Koes, and A. Burdorf. 2010. "Associations Between Work-Related Factors and Specific Disorders of the Shoulder – A Systematic Review of the Literature." *Scandinavian Journal of Work, Environment and Health* 36 (3): 189–201.

Weir, P. L., A. M. Holmes, D. M. Andrews, W. J. Albert, N. R. Azar, and J. P. Callaghan. 2007. "Determination of the Just Noticeable Difference (JND) in Trunk Posture Perception." *Theoretical Issues in Ergonomics Science* 8 (3): 185–199.